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THE SPECTRAL SHAPE OF THE GAMMA-RAY BACKGROUND FROM BLAZARS

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ABSTRACT

The spectral shape of the unresolved emission from different classes of gamma-ray emitters can be used to disentangle the contributions from these populations to the extragalactic gamma-ray background (EGRB). We present a calculation of the unabsorbed *spectral shape* of the unresolved blazar contribution to the EGRB starting from the spectral index distribution (SID) of resolved EGRET blazars derived through a maximum-likelihood analysis accounting for measurement errors. In addition, we explicitly calculate the *uncertainty* in this theoretically predicted spectral shape, which enters through the spectral index distribution parameters. We find that: (a) the unresolved blazar emission spectrum is only mildly convex, and thus, even if blazars are shown by GLAST to be a dominant contribution to the ERGB at lower energies, they may be insufficient to explain the EGRB at higher energies; (b) the theoretically predicted unresolved spectral shape involves significant uncertainties due to the limited constraints provided by EGRET data on the SID parameters, which are comparable to the statistical uncertainties of the observed EGRET EGRB at high energies; (c) the increased number statistics which will be provided by GLAST will be sufficient to reduce this uncertainty by at least a factor of three.

Subject headings: galaxies: active – gamma rays: observations – gamma rays: theory – diffuse radiation

1. INTRODUCTION

The isotropic, and presumably, extragalactic gamma-ray background emission (EGRB) detected by the Energetic Gamma-ray Experiment Telescope (EGRET) aboard the *Compton Gamma-ray Observatory* (Sreekumar et al. 1998) is one of the most important observational constraints on known or theorized populations of faint, unresolved gamma-ray emitters. With the imminent launch of the *Gamma-ray Large Area Space Telescope* (GLAST), which is expected to represent an unprecedented leap in observational capabilities in GeV energies, the timing is especially opportune to consider the information content of the diffuse background and methods for maximizing the scientific return from its study.

One of the primary challenges in using the EGRB to constrain properties of extragalactic gamma-ray emitters and exotic physics is disentangling the convolved contributions of guaranteed participating populations. Estimates of the levels of the collective unresolved emission even from established classes of extragalactic sources (such as blazars and normal galaxies) involve significant uncertainties and are at the order-of-magnitude level at best (e.g., Padovani et al. 1993; Stecker & Salamon 1996; Kazanas & Perlman 1997; Mukherjee & Chiang 1999; Mücke & Pohl 2000; Dermer 2006; Lichti et al. 1978; Pavlidou & Fields 2002).

A very promising approach for the study of the EGRB and its components is through the use of spectral shape information. Let us consider the optimal case where the expected spectral shapes of the unresolved emission from known classes of gamma-ray sources can be confidently predicted. In this case, a series of conclusions can be drawn regarding the potential contributions of these classes to the EGRB even without detailed calculations of the *magnitudes* of their collective emission. For example, in comparing the spectral shape of the spectrum due to a particular class with that of the EGRB, one can identify whether this class could, in principle, comprise most of the EGRB or require the existence of contributions from other classes (Stecker & Salamon 1996a,b; Strong et al. 2004; Pavlidou & Fields 2002)[4]. Potentially identifiable spectral features could be predicted and searched for in GLAST data (e.g., Pavlidou & Fields 2002). Finally, spectral information could be used to ultimately disentangle different components and contributions (as in e.g. de Boer et al. 2004 for the case of the diffuse emission from the Milky Way). An additional attractive feature of such calculations is that the associated uncertainties are largely independent of those entering the calculations of the overall unresolved emission flux.

As blazars are the most populated class of gamma-ray emitters, unresolved blazars are guaranteed to contribute significantly, if not dominantly, to the EGRB. Thus, it is especially important to understand the expected spectral shape of their collective unresolved emission and the uncertainties involved in its calculation. Individual blazars have been measured to have power-law spectra in the EGRET range, $F_E \propto E^{-\alpha}$, with spectral index α ranging approximately from 1.5 to 3. The unresolved emission from a collection of power-law emitters with variable spectral indices[5] has, invariably, a convex spectral shape (Brecher & Burbidge 1972; Stecker & Salamon 1996;

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[4] Note that the method of spectral comparison can only be used to *reject* a population from being the sole source of the EGRB; spectral consistency does not constitute in itself proof of the importance of a class of objects as an EGRB contributor, since the overall normalization of the emission may, in fact, be low depending on the gamma-ray luminosity function of the population.

[5] Statistically significant spread in the observed and intrinsic spectral index of blazars has also been confirmed in other energy

Pohl et al. 1997; Pavlidou et al. 2007). The exact shape of the unresolved spectrum depends on the spectral index distribution (SID) of gamma-ray loud blazars. Recognizing that this is the case, Stecker & Salamon (1996a) explicitly reconstructed a spectrum from the observed SID of blazars in the 2nd EGRET catalog (Thompson et al. 1995), deriving a spectrum that was indeed significantly convex. However, measurement errors in individual spectral indices smear the SID and exaggerate the curvature of the spectrum (Pohl et al. 1997).

Recently, in Venters & Pavlidou 2007 (hereafter VP07), we have applied a maximum-likelihood analysis to recover the intrinsic spectral index distribution (ISID) of gamma-ray loud blazars from EGRET observations. We found that (1) the maximum-likelihood ISID is appreciably narrower than the observed SID, so the best-guess spectrum is likely to have only a mild curvature; (2) BL Lacs and flat spectrum radio quasars (FSRQs) are likely to be spectrally distinct populations with spectrally distinct contributions to the EGRB; (3) there is no evidence for a systematic shift of spectral variability with flaring implying that although variability may be important in the level of the contribution from blazars, ignoring variability effects in spectral shape studies is likely to be a good approximation.

Here, we use the ISIDs derived in VP07 to calculate the spectral shape of the blazar contribution to the EGRB. We examine the sensitivity of the shape to the exact values of the ISID parameters and report on the range of possible shapes given our uncertainties in the determination of these parameters. We also investigate how the spectral shapes of the BL Lac and FSRQ contributions may differ. Finally, we predict how our understanding of the spectral shape of the unresolved blazar emission will improve after GLAST observations become available.

2. FORMALISM

If the differential photon flux spectrum of a single blazar is $F_E(E) = F_{E,0}(E/E_0)^{-\alpha}$ (photons per unit area per unit energy per unit time), then the total flux of photons with energies $> E_0$ is $F(> E_0) = F_{E,0}E_0/(\alpha - 1)$ (photons per unit area per unit time). The contribution of a single unresolved blazar of $F(> E_0) = F$ to the EGRB is

$$I_1 = (\alpha - 1)\frac{F}{4\pi E_0}\left(\frac{E}{E_0}\right)^{-\alpha} \tag{1}$$

where I has units of photons per unit area per unit energy per unit time per unit solid angle, and the flux of one source is uniformly distributed over 4π.

Now let us assume that the flux distribution of unresolved blazars (number of objects per flux interval) can be described by a function $g(F)$; and that the distribution of spectral indices (number of objects per spectral index interval) can be described by a function $p(\alpha)$. Then the total contribution of unresolved blazars to the EGRB is

$$I_{\rm EGRB}(E) = \int_{\alpha=-\infty}^{\infty} d\alpha \int_{F=0}^{F_{\rm min}} dF\, g(F) I_1 p(\alpha)\,. \tag{2}$$

In Eq. (2), $F_{\rm min}$ is the minimum flux of an object that can be resolved by the telescope under consideration.

bands (see e.g. Shen et al. 2006 for the case of X-ray emission).

We now make the assumptions that (a) blazar spectra can be adequately described by single power-laws in the observed energy range, as well as at energies which redshift down to the observed range; (b) the flux distribution is independent of spectral index; and (c) the spectral index does not evolve with time and does not depend on luminosity. In this case, blazars in any single flux interval sample an identical SID, and produce the same fraction of photons in any two energy bins, thus resulting in a unique spectral shape. This is intuitively reasonable. Had the (non-evolving) ISID been a δ-function, all blazars would be power laws of the same slope, independently of the epoch of observation and the coadded spectrum would identically be a power law of the same slope. Since our ISID is a Gaussian of non-evolving spectral indices, the spectral shape is curved, but still independent of the luminosity function. The blazars in a specific unresolved flux interval contributing to the background will represent a mixture of luminosities and redshifts, but since the blazar properties that determine the flux interval (redshift, luminosity) do not depend on the spectral index, the blazars within that flux interval will fairly sample the same ISID. Additionally, redshifting down the spectra has no effect on the slope for single power laws as long as no absorption occurs. The same reasoning is applicable to all flux intervals, which therefore contribute portions of the background that have different amplitude but the same, unique spectral shape, dependent only on the parameters of the ISID.

The magnitude and spectral shape factors in Eq. (2) therefore decouple under our assumptions, and Eq. (2) can be rewritten as

$$I_{\rm EGRB}(E) = I_0 \int_{\alpha=-\infty}^{\infty} d\alpha (\alpha - 1)\left(\frac{E}{E_0}\right)^{-\alpha} p(\alpha)\,, \tag{3}$$

where I_0 is a normalization constant depending on the flux distribution of unresolved blazars. If $p(\alpha)$ is Gaussian, as assumed in VP07, then Eq. (3) is analytically integrable (Pavlidou et al. 2007).

It should be noted that if the above assumptions do not hold, then the spectral shape may not decouple from its magnitude as above. This is particularly true if features are present in blazar spectra (breakdown of assumption a). However, there is no evidence in EGRET data for such features. In the cases where the other two assumptions (b and c) do not hold, as long as the dependencies are small, the decoupling of the shape and magnitude will still be approximately correct. In VP07, possible correlations between spectral index and redshift and between spectral index and luminosity for blazars were investigated and no evidence for such correlations was found. Nevertheless, absence of evidence is not equivalent to evidence of absence of a correlation, and it cannot, as yet, be proven that the spectral index is independent of redshift and luminosity. Since the gamma-ray emission from blazars is likely due to Inverse Compton emission which is related to emission at lower frequencies, a relationship between the gamma-ray spectral index and the gamma-ray luminosity is plausible and can be motivated, for example, in the context of the blazar sequence (Fossati et al. 1998; Ghisellini et al. 1998). On the other hand, the blazar sequence has been subsequently called into question with data from deeper blazar surveys (Giommi et al. 2005; Padovani 2007). Thus, it is difficult to inter-

pret the VP07 result, especially based on current data alone; a further investigation of the blazar sequence (as suggested in Maraschi et al. 2007) as well as posible correlations of luminosity with spectral index in the GeV energy range with GLAST data will offer further insight into the issue. However, we point out that systematic uncertainties in the spectral shape of the blazar contribution entering through correlations between blazar spectral index and blazar luminosity/redshift *weaker* than the VP07 constraints would be dominated by the uncertainties entering through our limited knwoledge of the ISID, or the systematic uncertainties in the observational determination of the EGRB.

For now, we can instill more confidence in the reasoning behind the above arguments by applying our formalism to an independent SID for which a shape was determined using the full redshift-dependent, luminosity-dependent equation. We applied Eq. 3 to the Stecker & Salamon (1996a) SIDs[6] and found the shapes for flaring and quiescent blazars reported by the authors (although, of course, our formalism cannot reproduce the *amplitude* of the emission they reported).

3. INPUTS

Traditionally, in order to evaluate the blazar contribution to the EGRB, one would derive a gamma-ray luminosity function and a redshift distribution and calculate the overall *magnitude* of the contribution. However, in this analysis, we seek information about the *shape* of the blazar contribution rather than the overall magnitude. Thus, our only inputs are the ISIDs for different EGRET samples and simulated GLAST samples presented in VP07. Since we do not include information about the magnitude of the blazar contribution to the EGRB, we have normalized our curves so that they always pass through the 83 MeV best-guess measurement of the EGRB from EGRET data ($E^2 I_{\rm EGRB}|_{83\,{\rm MeV}} = 1.5 \times 10^{-6}\,{\rm GeV\,cm^{-2}s^{-1}sr^{-1}}$), as analyzed by Strong et al (2004), in order to aid the visual comparison with the observed EGRB shape. This normalization is completely arbitrary as we could have instead chosen any one of the Strong et al. 2004 data points; we have chosen 83 MeV since at this energy the observational statistical and systematic uncertainties are relatively low.

4. RESULTS

The spectral shape of the unresolved blazar emission for the ISID of the Mattox et al. (2001) confident blazars sample (46 sources) is plotted in Fig. 1. The solid line is the best-guess spectrum based on the maximum-likelihood Gaussian ISID for this sample (mean $\alpha_0 = 2.27$ and spread $\sigma_0 = 0.2$) from VP07. The gray region represents spectral shapes derived from (α_0, σ_0) pairs within the 1σ contour of the ISID parameter likelihood and illustrates our 1σ uncertainty in the unresolved blazar spectral shape. For comparison, we also plot datapoints with (statistical) errors for the Sreekumar et al. (1998) (open circles) and the Strong et al. (2004) (filled triangles)[7] determinations of the EGRB from EGRET data. We stress again that our results are intended to be compared to the EGRET data only in shape (relative intensity between different energy bins) and not in amplitude, since the normalization of our curves does not carry any information. The thick dotted lines indicate the Strong et al. (2004) systematics, entering through their model of the Galaxy. The best-guess spectrum is only mildly curved in comparison to the best-guess spectrum derived from the observed, measurement-error–contaminated SID (as parametrized by Stecker & Salamon 1996a for the Mattox et al. 2001 confident blazar dataset; shown as the thin dashed line in Fig. 1) in lieu of the maximum-likelihood ISID.

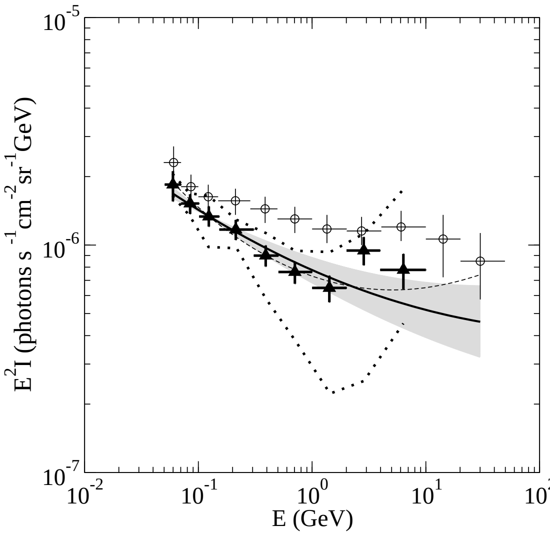

Fig. 1.— Spectral shape of the unresolved blazar emission. All curves have been normalized (arbitrarily) so that they pass through the 83 MeV point of the Strong et al. (2004) EGRB. Solid line: best-guess spectrum based on a maximum-likelihood ISID determined using the Mattox et al. 2001 confident blazar sample. Grey region: spectral shapes allowed for ISID parameters within the 1σ likelihood contour. Filled triangles: Strong et al. (2004) EGRB determination. Open circles: Sreekumar et al. (1998) EGRB determination. Error bars are statistical errors only. Thick dotted lines: Strong et al. (2004) EGRB systematics. Thin dotted line: SID determined in Stecker & Salamon (1996a).

A most important result is that the constraints on the theoretical cumulative blazar spectrum are not very strong. In fact, the theoretical uncertainties in the spectrum entering through our limited understanding of the ISID are comparable with the statistical uncertainties (errors on individual data points) in the observed EGRB. Worse yet, the large systematic and statistical uncertainties in the determination of the EGRB impede any comparison between the theoretical cumulative blazar spectrum and the EGRB. For this reason, no strong conclusions regarding the spectral (in)consistency of the blazar collective spectrum with the observed EGRB should be drawn based solely on EGRET data. Note that improvements in observations will *not* automatically alleviate this concern. Even if the systematic and statistical uncertainties in the data improve, if the uncertainties in the theoretical spectral shape remain as they are, strong

[6] Note that appropriate adjustments had to be made: (1) separation between flaring and quiescent blazars as they did, and (2) rejection of unphysical spectral indices arising from a wide SID.

[7] The Sreekumar et al. (1998) and the Strong et al. (2004) EGRB determinations differ in the model used to subtract the diffuse emission of the Milky Way with the difference resulting from the fact that the Strong et al. (2004) determination is based on a Milky Way model which accounts for the GeV excess.

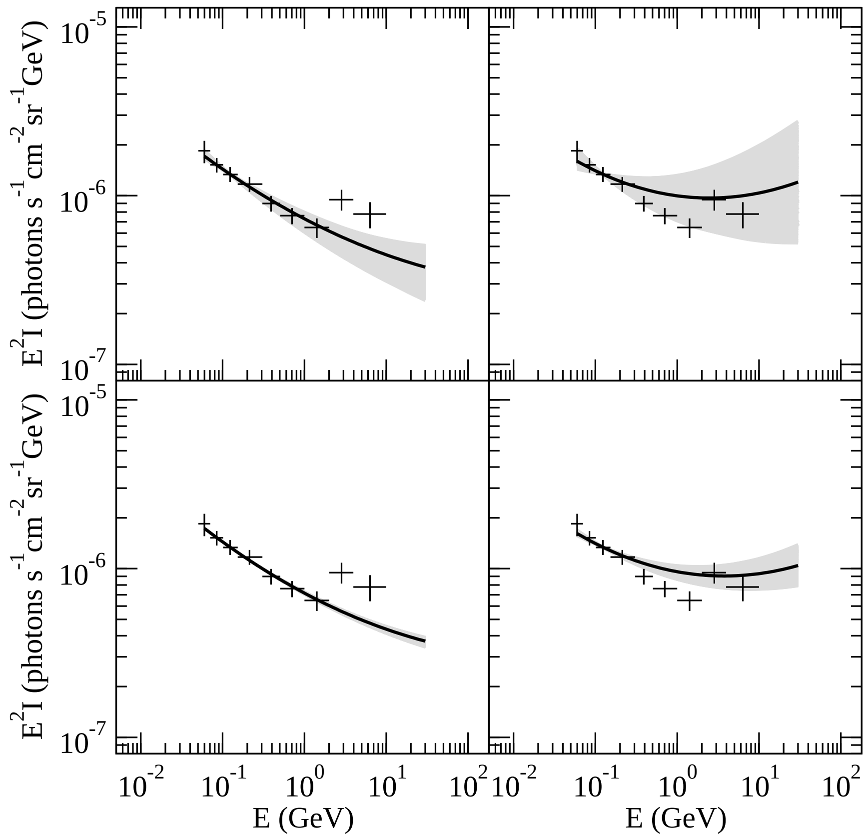

Fig. 2.— Predicted spectral shapes for FSRQs (left column) and BL Lacs (right column). All curves have been normalized (arbitrarily) to the 83 MeV point of the Strong et al. EGRB. Solid lines represent the best-guess spectra and the gray regions, the 1σ spectral shape uncertainties. Data points: Strong et al. (2004) EGRB determination (error bars represent statistical errors). Upper panel: EGRET data. Lower panel: reduction of shape uncertainties in the GLAST era based on the Dermer (2007) predictions for the numbers of detectable BL Lacs and FSRQs.

conclusions about the blazar contribution to the EGRB will remain unattainable. However, if we were to ignore systematics and take at face-value the upturn of the EGRET EGRB at high energies indicated by Strong et al. (2004), our results suggest that it is unlikely that EGRET blazars, as a population, comprise the dominant contribution to the background at the highest energies even if they do dominate at low energies.

If BL Lacs and FSRQs have distinct intrinsic spectral index distributions as indicated tentatively by EGRET data (Pohl et al. 1997; Mukherjee et al. 1997; VP07), their cumulative unresolved spectra will also differ. The top row of Fig. 2 shows the spectral shapes of unresolved emission from FSRQs (left panel) and BL Lacs (right panel) calculated from the respective VP07 ISIDs derived from EGRET data. The solid lines again represent best-guess spectra and the gray regions are 1σ uncertainties in the shape. The observed EGRB shape (Strong et al. 2004 with statistical error bars) is indicated with the crosses.

The best-guess spectra of the two populations have different shapes with the cumulative emission from BL Lacs being generally harder than that of FSRQs and having a more convex spectrum. However, due to the poor number statistics of BL Lacs, their ISID is not well constrained and this uncertainty is carried over to the emission spectrum: the theoretical uncertainties in the unresolved BL Lac spectral shape are much larger than the statistical uncertainties in the data and comparable with the systematic uncertainties in the observed EGRB. Thus, no confident statement can be made regarding the spectral (in)consistency of BL Lacs with the observed EGRB. On the other hand, as there are many more FSRQs than BL Lacs detected by EGRET, when all blazars are treated as a single population, both the ISID and the unresolved emission spectrum closely resemble that of FSRQs.

If a similar ratio of FSRQs to BL Lacs is also present in the unresolved blazar population (e.g., Dermer 2007) as in the resolved EGRET blazar population, the shape of the blazar EGRB component will mostly resemble that of Fig. 1. If on the other hand the BL Lac fraction is much higher in unresolved blazars (e.g. Pohl et al. 1997), then there may be an appreciable BL Lac contribution to the EGRB, accounting, at least in part, for the upturn of the observed EGRB tentatively suggested by EGRET data. GLAST observations will greatly help in addressing this question as it is expected to resolve between 1000 and 10,000 blazars, thus placing much stronger constraints on the luminosity function and evolution of FSRQs and BL Lacs.

GLAST observations will also allow a much more confident determination of the FSRQ and BL Lac ISIDs resulting in corresponding improvements in the determinations of the unresolved emission spectral shapes for these

populations. The lower row in Fig. 2 shows the improvements of our theoretical predictions for the FSRQ (left panel) and BL Lac (right panel) unresolved spectra using ISIDs from the simulated GLAST datasets of VP07. Note that this is simply a prediction of how much the uncertainties in the determinations of the spectral shapes will be reduced with increased number statistics and is not an actual prediction of the GLAST EGRB. Shape uncertainties in the GLAST era are reduced by a factor of ~ 3. FSRQs and BL Lacs were assumed to follow the Dermer (2007) luminosity functions which represent the most conservative (lowest) predictions for the number of blazars that will be resolved by GLAST. Note that the Dermer luminosity functions were *not* used to determine the spectral shapes but solely to predict the numbers of BL Lacs and FSRQs GLAST will see, and thus, allowing us to estimate the reduction in the uncertainties on the ISIDs. If more blazars are, in fact, detected by GLAST, the ISIDs will be determined with even greater confidence due to improved number statistics. Even in the most conservative case, it is clear that GLAST observations will place very tight constraints on the expected spectral shapes of the unresolved emission of gamma-ray emitters - at least in the case of blazar classes. Additionally, GLAST should also be able to further constrain the EGRB itself. Thus, in light of GLAST, the spectral shapes of the contributions of blazar populations would provide vital information about whether those populations could, in principle, explain all of the EGRB, or whether contributions from other gamma-ray emitters are required.

5. DISCUSSION

We have calculated the expected spectral shape of the unresolved gamma-ray emission from blazars under the assumptions that the ISIDs of blazars do not evolve with redshift and are independent of blazar luminosity and flaring state. We have also explicitly calculated the 1σ uncertainty in the spectral shape entering through the limited constraints on the blazar ISIDs derived from EGRET data. Finally, we have predicted by how much these uncertainties will be reduced if GLAST observations are used to determine the blazar ISIDs.

The unresolved emission spectral shape can be used as an indicator of the potential importance of a given population's contribution to the EGRB, and it constrains the maximal contribution at high energies relative to that at low energies. If the curvature tentatively seen in the observed EGRB is real, then a population with little such curvature in its unresolved spectrum (such as the FSRQs) will not be the dominant contributor to the EGRB at high energies even if it is dominant at low energies. The unresolved BL Lac spectrum does seem to be more convex than that of the FSRQs, but the level of uncertainty in the spectral shape is high in this case because only a few BL Lacs were detected by EGRET. However, GLAST observations will dramatically improve our understanding of the blazar ISIDs and the associated unresolved spectral shapes allowing us to use spectral shape information to calculate the minimal additional contribution required from other classes of sources to explain the observed EGRB spectrum.

It should be stressed that here we have only calculated *unabsorbed* spectra. At energies higher than 10 GeV, gamma-ray absorption through interactions (pair production) with the extragalactic background light becomes important (e.g., Salamon & Stecker 1998), and the spectral shape of any contribution to the EGRB will be accordingly changed. We will return to this effect in a future publication.

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